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Abstract Volcanic sills and dikes inferred from seismic reflection profiles and geophysical studies of the Ross Sea are thought to be related to the rift basins in the region, and their emplacement to be coeval with extension. However, lack of precise geochronology in the Terror Rift of the Ross Sea region has left these inferred relationships poorly constrained and has hindered neotectonic studies, because of the large temporal gaps between seismic reflectors of known ages. New ^{40}Ar/^{39}Ar geochronology presented here for submarine volcanic rocks provides better age constraints for neotectonic interpretations within the Terror Rift. Several samples from seamounts yielded young ages between 156 ± 21 and 122 ± 26 Ka. These ages support interpretations that extension within the Terror Rift was active at least through the Pleistocene. Three evenly spaced samples from the lowermost 100 m of Franklin Island range in age from 3.28 ± 0.04 to 3.73 ± 0.05 Ma. These age determinations demonstrate that construction of a small volcanic edifice such as Franklin Island took at least several hundred thousand years, and therefore that much larger ones in the Erebus Volcanic Province are likely to have taken considerably longer than previously inferred. This warrants caution in applying a limited number of age determinations to define the absolute ages of events in the Ross Sea region.

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Introduction

The most recent phase of extension in the West Antarctic Rift System (WARS) is thought to have begun in the Eocene (Salvini et al., 1997; Rossetti et al., 2000). However, timing for the end of this extension has remained in question. Initial phases of magmatic activity in the WARS began in northern Victoria Land at ~48 Ma as pluton and dike intrusions (Rocchi et al., 2002), and numerous studies have documented dikes with ages between 40 Ma (Rossetti et al., 2000) and 35 Ma (Kyle, 1990a). Volcanism in the Royal Society Range (Kyle, 1990b), north of Mt Morning, and the eastern edge of Minna Bluff (Rocchi et al., 2002) at ~14 Ma represent the onset of activity in the Erebus Volcanic Province much farther to the south. At ~4 Ma, volcanism became more widespread and extended eastward towards Ross Island and into the Ross Sea (Kyle, 1990b). Although present day, large-scale continental rifting appears unlikely when using global plate reconstructions (Steinberger et al., 2004), extremely young volcanism (< 10 Ka) at either end of the Terror Rift (Mt Melbourne to the north and Mt Erebus to the south) suggests that extension across the Terror Rift may still be active today (Armstrong, 1978; Esser et al., 2004). The lack of data from the Ross Sea has left a gap in our understanding of the eruption history of lavas between the Melbourne and Erebus Volcanic Provinces, and whether the localities and migration of this volcanism are controlled by tectonic processes. Although geophysical evidence is improving interpretations of extension across the Terror Rift, time constraints for these events in the Victoria Land Basin are limited by the lack of precise, absolute geochronology.

Geologic background

Widespread submarine volcanism in the Ross Sea has long been inferred from seismic reflection profiles and from magnetic and gravitational anomalies observed in geophysical studies (Behrendt, 1987; Behrendt et al., 1991). Trey et al. (1999) noted that these volcanic bodies are often associated with the axes of rift basins, and therefore are probably coeval with rifting. The Cape Roberts Project (CRP) provided some age constraints on prominent seismic reflectors in the Victoria Land Basin (e.g., Henrys et al., 2001). However, a substantial succession of strata mapped seismically in the offshore portion of the basin was unsampled by CRP drilling (Fielding et al., 2006). The age of the uppermost CRP strata is 17 Ma, suggesting that the overlying strata are Miocene and younger in age. Widespread faults and volcanic rocks crosscut this stratigraphic succession along the Terror Rift (Cooper et al., 1987; Hall, 2006). Dating these submarine volcanic rocks from the Ross Sea holds the promise to provide better age constraints on the onset of this most recent stage of extension in the Terror Rift.

The only age determination from volcanic rocks within the offshore Terror Rift was completed by Armstrong (1978) using the K-Ar method on a single sample from Franklin Island, obtaining an imprecise age of 4.8 ± 2 Ma (2 σ). Most of the dated volcanism in the Erebus Volcanic Province lies to the south of the actual Terror Rift and may not be representative of activity farther to the north, leading several authors to rely on the poorly known age of Franklin Island to indirectly date volcanism within the Terror Rift (Cooper et al., 1987; Fielding et al., 2006). The interfingering nature of volcanic rocks as shown on seismic reflection profiles

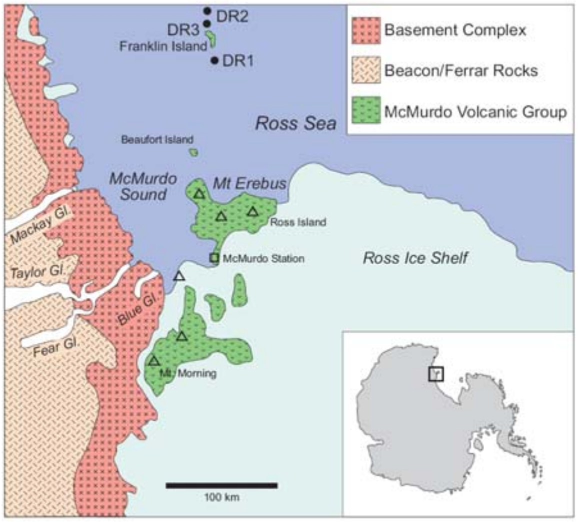

Figure 1. Map of the western Ross Sea region showing dredge locations and Franklin Island. Bedrock geology is simplified after Warren (1969).

allows their ages to be used as constraints for the youngest strata. Both these igneous features and faults also cross cut the seafloor supporting the hypothesis that both are younger in age than the youngest strata. Precise age determinations from Franklin Island and Ross Sea seamounts would, therefore, provide better constraints on both the evolution of volcanic activity in the Erebus Volcanic Province and extension in the Terror Rift.

Samples and methods

Subaerial samples were collected from a variety of locations on Franklin Island. The stratigraphy of Franklin Island is comprised of complex interbedded lava flows and tuffs, parasitic cones, and cross-cutting dikes (Ellerman and Kyle, 1990). Basanitic samples were taken from low-level, mid-level, and upper-level flows in the interval between sea level and approximately 100 m elevation. Additional samples were taken from a Hawaiite dike crosscutting the overlying hyaloclastites. These samples represent only a portion of the volcanic activity on Franklin Island. Specific samples from these localities were selected for $^{40}Ar/^{39}Ar$ analysis based on minimal alteration and lowest abundance of vesicles.

Submarine samples were also collected by members of the 2004 NBP04-01 geophysical cruise on the RVIB N.B. Palmer from several dredge locations within the Ross Sea (Wilson et al., 2004). High cable-tensions during dredging and the presence of at least one fresh surface were used to identify samples taken *in-situ* from the seamounts. This prevents material that may have been glacially deposited from being included in the geochronological study. Basaltic flows were preferentially chosen over hyaloclastites or more scoriaceous material, in order to reduce the risk of contamination by secondary alteration or seawater interaction.

Due to the lack of suitable mineral phases, argon analysis was completed on sample chips of glassy to very fine grained matrix material. Although mantle xenoliths are abundant throughout the Erebus province, xenocrystic phases are predominantly olivine and orthopyroxene, both low potassium phases, which are unlikely to affect argon analysis. Nonetheless, careful sample preparation was used to ensure that only fine grain groundmass material was used in analysis as an added precaution against xenocrystic contamination. Chips (approximately 1.5 mm in size) were encapsulated in foil and irradiated at the McMaster University research reactor. Analysis was completed through laser step-heating in the Argon Geochronology Laboratory at the University of Michigan, following the methods outlined by Streepey et al. (2000). Simultaneous analysis of K, Ca, and Cl monitored potential contributions from alteration products or melt inclusions to the ^{40}Ar budget. Biotite from the Fish Canyon Tuff, FCT-3 with an age of 27.99 Ma, was used as the neutron flux monitor.

$^{40}Ar/^{39}Ar$ ages were calculated for the total gas and also for each degassed fraction to produce plateau spectra as well as isochrons (Fig. 2). A higher $^{40}Ar/^{36}Ar$ intercept than atmospheric argon in several samples suggests that extraneous argon may introduce errors into plateau ages which assume an initial $^{40}Ar/^{36}Ar$ of 295.5. For this reason, the isochron method was preferred for calculating

Table 1 $^{40}Ar/^{39}Ar$ age determinations

Sample	Total Gas Age, Ma	Plateau Age, Ma	^{39}Ar Plateau %	Isochron Age, Ma	MSWD	$^{40}Ar/^{36}Ar$ Intercept	Preferred Age
04ANT1-6	3.53 ± 0.04	None	-	3.28 ± 0.04	2.65	304.1± 1.8	3.28 ± 0.04
04ANT1-9	3.47 ± 0.02	3.40 ± 0.02	92.3	3.38 ± 0.04	1.18[a]	297.3 ± 3.3	3.40 ± 0.02
04ANT5A-19	3.75 ± 0.04	3.73 ± 0.05	95	3.68 ± 0.16	2.32[a]	297.4 ± 6.3	3.73 ± 0.05
DRE1-31	0.131 ± 0.026	0.133 ± 0.024	100	0.158 ± 0.047	1.22[a]	293.0± 4.0	0.133 ± 0.024
DRE1-32	0.192 ± 0.018	0.167 ± 0.015	100	0.122 ± 0.026	0.55[a]	308.2 ± 6.1	0.122 ± 0.026
DRE3-73	0.173 ± 0.026	0.156 ± 0.021	100	0.089 ± 0.066	1.36[b]	307.6 ± 11.1	0.156 ± 0.021

[a] Isochron is defined by only plateau points.
[b] Less than 50% radiogenic ^{40}Ar. Plateau age preferred over isochron.

the $^{40}Ar/^{39}Ar$ ages of these samples. However, the plateau method was used for samples which yielded less than 50% radiogenic Ar. One sigma errors are reported for ages from both methods.

Results

New $^{40}Ar/^{39}Ar$ ages for Franklin Island range from 3.28 to 3.73 Ma. The sample collected just above sea level, 04ANT5A-19, yielded the oldest age of 3.73 ± 0.05 Ma (1 σ). A mid-level flow, sample 04ANT1-9, yielded an age of 3.38 ± 0.04 Ma. The cross-cutting dike yielded the youngest measured age of 3.28 ± 0.04 Ma. Although these dates are within error of the original Armstrong (1978) K-Ar age of 4.8 ± 2 Ma, they are of higher precision and provide more constraints on the age ranges of activity.

New dates from samples dredged from the sea floor near Franklin Island yield significantly younger ages. Two samples from Dredge 1 (76˚ 17.24´ S, 168˚ 20.5´ E) yielded ages of 133 ± 24 Ka (DRE1-31) and 122 ± 26 Ka (DRE1-32), giving an average age of 127 Ka. These ages are significantly younger than the previously assumed age for Franklin Island, which as shown above was based on a single K-Ar age determination. One sample from Dredge 3 (75˚ 58.22´ S, 168˚ 12.70´ E) yielded a similar, yet slightly older age of 156 Ka.

Discussion

The new ages from Franklin Island suggest that emplacement of the island was more gradual than interpreted for other edifices in the Erebus Volcanic Province. For example, the entire emplacement of the much larger Mt. Erebus is hypothesized to have taken place in under 1 m.y., and other main edifices are thought to have been active for only 1-2 m.y. (Kyle, 1990b). The three subaerial samples analyzed in this study represent only 100 m of section of Franklin Island and yet span a half a million years. Younger ages can be assumed for the flows at elevations higher than 100 m and older ages for the additional 400 m of material present below sea level, using principles of relative dating. This suggests that the volcanism has occurred for significantly longer than the measured 0.5 m.y., and caution should therefore be exercised in reconstructing the eruption history of individual volcanoes and of the province as a whole using only a meager number of high-precision age determinations.

The young ages observed from sea floor volcanic rocks represent a continuation of activity in the offshore region between the Melbourne and Erebus Volcanic Provinces. Estimates for the formation of Franklin Island are consistent with the interpretation that volcanism is younger in the Ross Sea than in the Royal Society Ranges and northern Victoria Land. Seafloor volcanism is much younger suggesting that magmatic activity is continuing in new edifices as extension continues.

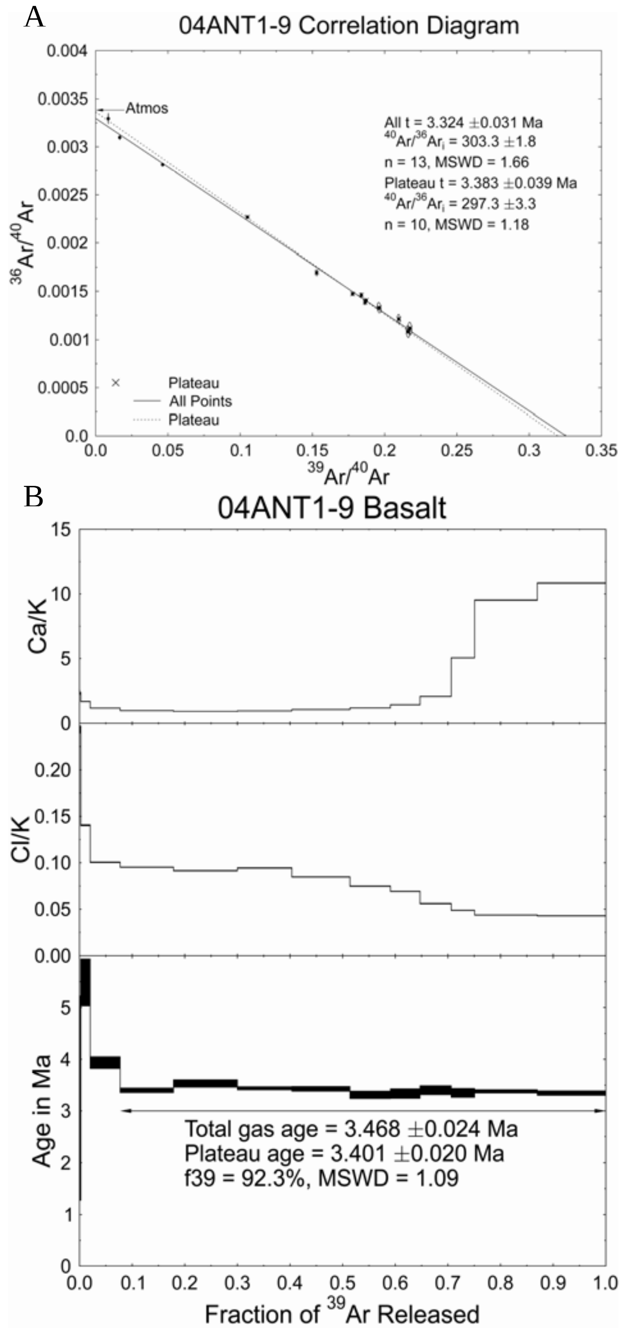

Figure 2. Example of isochron and plateau age plots. A) All points were plotted, as well as just the plateau points. $^{36}Ar/^{40}Ar$ matches atmospheric values ($^{40}Ar/^{36}Ar$ = 295.5), so the plateau age was used for this sample. B) Plateau spectrum diagram illustrating the relationship of the ^{39}Ar gas fractions released during laser-step heating. We interpret increases in Ca/K to be due to clinopyroxene degassing, which is not accompanied by any changes in age for any of the gas fractions.

Summary

The Terror Rift appears to be active or was active until very recently as shown by the crosscutting nature of these young volcanic rocks. Seamounts as young as 122 Ka represent volcanic rocks cutting the entire Terror Rift section up to the seafloor, and unsampled areas may be even younger. If volcanic activity is coeval with rifting, we can deduce that extension continued at least until the latest Pleistocene and probably to recent times. Improved understanding of the geochronology of seafloor volcanic rocks not only aids in models of magmatic evolution, but will assist in seismic interpretations and neotectonic studies by providing absolute and precise time constraints for Terror Rift basin strata and structures.

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References

Armstrong R. L. (1978), K-Ar dating: Late Cenozoic McMurdo Volcanic Group and dry valley glacial history, Victoria Land, Antarctica, New Zealand of Geology and Geophysics, 21(6), 658-698.

Behrendt, J.C. (1990), Ross Sea, Antarctic Research Series, 48, 89-90.

Behrendt, J.C., W.E. LeMasurier, A.K. Cooper, F. Tessensohn, A. Trehu, and D. Damaske (1991), Geophysical studies of the West Antarctic rift system, Tectonics, 10(6), 1257–1273.

Cande, S.C., and J.M. Stock (2006), Antarctica: Contributions to global earth sciences. "Constraints on the Timing of Extension in the Northern Basin", Ross Sea, p. 319-326.

Cooper, A.D., F.J. Davey, and J.C. Behrendt (1987), Seismic stratigraphy and structure of the Victoria Land Basin, western Ross Sea, Antarctica. *In The Antarctic Continental Margin: Geology and Geophysics of the Western Ross Sea*, Circum-Pacific Council of Energy and Mineral Resources. Earth Sci. Ser., 5B, (ed. A.K. Cooper and F.J. Davey), p. 27-65.

Ellerman, P.J., and P.R. Kyle (1990), Franklin Island, Antarctic Research Series, 48, 91- 93.

Esser, R.P., P.R. Kyle, and W.C. McIntosh (2004), Ar-40/Ar-39 dating of the eruptive history of Mount Erebus, Antarctica: volcano evolution, Bulletin of Volcanology, 66(8), 671-686.

Fielding, C.R., S.A. Henrys, and T.J. Wilson (2006), Rift History of the Western Victoria Land Basin: A new Perspective Based on Integration of Cores with Seismic Reflection Data *In Antarctica: Contributions to global earth sciences*, (ed. D.K. Damaske, G. Kleinschmidt, H. Miller, and F. Tessensohn), p. 309-318, Springer-Verlag.

Hall, J.M. (2006) Structural evolution of the Terror Rift, Western Ross Sea, Antarctica: interpretation from 2D reflection seismic, Master's Thesis, The Ohio State University, Columbus, Ohio.

Henrys, S.A., C.J. Buecker, F. Niessen, and L.R. Bartek (2001) Correlation of seismic reflectors with the CRP-3 drillhole, Victoria Land Basin, Antarctica, Terra Antarctica, 8(3), 127-136.

Kyle, P.R (1990a), McMurdo Volcanic Group, western Ross Embayment, introduction, Antarctic Research Series, 48, 19-25.

Kyle, P.R. (1990b), Erebus Volcanic Province, Antarctic Research Series, 48, 81-88.

Rocchi, S., P. Armienti, M. D'Orazio, S. Tonarini, J.R. Wijbrans, and G. DiVencenzo (2002), Cenozoic magmatism in the western Ross Embayment: Role of mantle plume versus plate dynamics in the development of the West Antarctic Rift System, Journal of Geophysical Research, 107(B9), 2195.

Rossetti, F., F. Storti, and F. Salvini (2000), Cenozoic noncoaxial transtension along the western shoulder of the Ross Sea, Antarctica, and the emplacement of McMurdo dyke arrays, Terra Nova, 12(2), 60-66.

Salvini, F., G. Brancolini, M. Busetti, F. Storti, F. Mazzarini, and F. Coren (1997), Cenozoic geodynamics of the Ross Sea region, Antarctica: Crustal extension, intraplate strike-slip faulting, and tectonic inheritance, Journal of Geophysical Research, 102(B11), 24,669 – 24,696.

Steinberger, B., R. Sutherland, and R.J. O'Connell (2004) Prediction of Emperor-Hawaii seamount locations from a revised model of global plate motion and mantle flow, Nature, 430, 167- 173.

Streepey, M.M., B.A. van der Pluijm, E.J. Essene, C.M. Hall, and J.F. Magloughlin (2000) Late Proterozoic (ca. 930 Ma) extension in eastern Laurentia, GSA Bulletin, 112(10), 1522 – 1530.

Trey, H., A.K. Cooper, G. Pellis, B. Della Vedova, G.R. Cochrane, G. Brancolini, and J. Makris (1999) Transect across the West Antarctic rift system in the Ross Sea, Antarctica, Tectonophysics, 301(1-2), 61-74.

Wilson, T. J., L. A. Lawver, S. A. Henrys, S. Mukasa, H. Horgan, M. Weiderspahn, M. Davis, J. Whittaker, A. Lowe, and M. Watson (2004) Cruise Report NBP0401 19 January to 18 February 2004 - McMurdo Station to McMurdo Station, Ross Sea, Antarctica, Institute of Geological and Nuclear Sciences Science Report 2004/03, p. 85.